GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL

[ ] REVISION NO. ____

Project No. A-3017 — DATE: 8/13/81

Project Director: Harris T. Johnson — ~~School~~/Lab EDL/IED

Sponsor: Whiting Corporation, Trackmobile Division

Type Agreement: Purchase Order No. 201063 dated 7/13/81

Award Period: From 7/15/81 To ~~8~~ 9/15/81 (Performance) 8/15/81 (Reports)

Sponsor Amount: $685.00 — Contracted through:

Cost Sharing: N/A — GTRI/~~GIT~~

Title: Pinion Shaft Fracture Analysis

ADMINISTRATIVE DATA — OCA CONTACT Faith G. Costello

1) Sponsor Technical Contact: -See Below-

2) Sponsor Admin./Contractual Contact: Gary Quedens, Whiting Corporation, Trackmobile Division, 1602 Executive Dr., LaGrange, GA 30240 Ph: 884-6651 ext 299

Reports: See Deliverable Schedule — Security Classification: N/A

Defense Priority Rating: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirement

Travel: Foreign travel must have prior approval - Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A

COMMENTS:

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 12/14/81

Project Title: Pinion Shaft Fracture Analysis

Project No: A-3017

Project Director: Harris T. Johnson

Sponsor: Whiting Corporation

Effective Termination Date: 9/15/81

Clearance of Accounting Charges: 9/15/81

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice ~~and Closing Documents~~
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Assigned to: EDL/IED ~~(School/~~Laboratory)

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FORM OCA 10:781

A-3017

Georgia Institute of Technology

ENGINEERING EXPERIMENT STATION

ATLANTA, GEORGIA 30332

ENGINEERING EXTENSION LABORATORY

West Georgia Area Office
P. O. Box 676
201 Tanner Street
Carrollton, Georgia 30117
Area Code 404/834-1480

September 9, 1981

Mr. Gary Quedens
Whiting Corporation
1602 Executive Drive
LaGrange, GA 30240

Dear Gary:

Enclosed is the final report on project A-3017 which concerns the fatigue analysis on your pinion shaft. I regret we took so long but, as I previously mentioned, the delay was caused by waiting on parts for our microprobe.

The primary cause of failure was reverse tortional fatigue. As the accompanying article discussed this is a distributed stress over several potential failure mechanisms, the weakest of which fails first.

In this case the weakest link is the stress concentration caused by the small radius at the base of the splines.

I trust this fills your requirement and again we thank you for the opportunity to serve you. Should you have future needs, please let me know.

Sincerely,

Harris T. Johnson, Director
West Georgia Area Office

WHITING CORPORATION

TRACKMOBILE DIVISION

FINAL REPORT
A-3017

FRACTURE ANALYSIS

ANALYSIS OF A FRACTURED DRIVE PINION

A fractured drive pinion belonging to the Whiting Corporation was examined by this laboratory and the cause of failure determined to be reversed torsional fatigue due to the sharpness of the radius at the base of the spline teeth. Analysis of the elemental content and hardness tests were also run and found to conform with specification as stated on Whiting Corporation's Research and Development Drawning No. Z2-0318.

A section was cut from the spline end opposite the fracture surface and polished for hardness measurements and elemental analysis. Hardness measurements were made on a Knoop indentation hardness tester and a carbon content trace made on the electron probe microanalyzer. The results of these tests are shown in Graph 1. An elemental analysis was run in the electron probe on an area near the center of the section. The results of this analysis are shown in the following table.

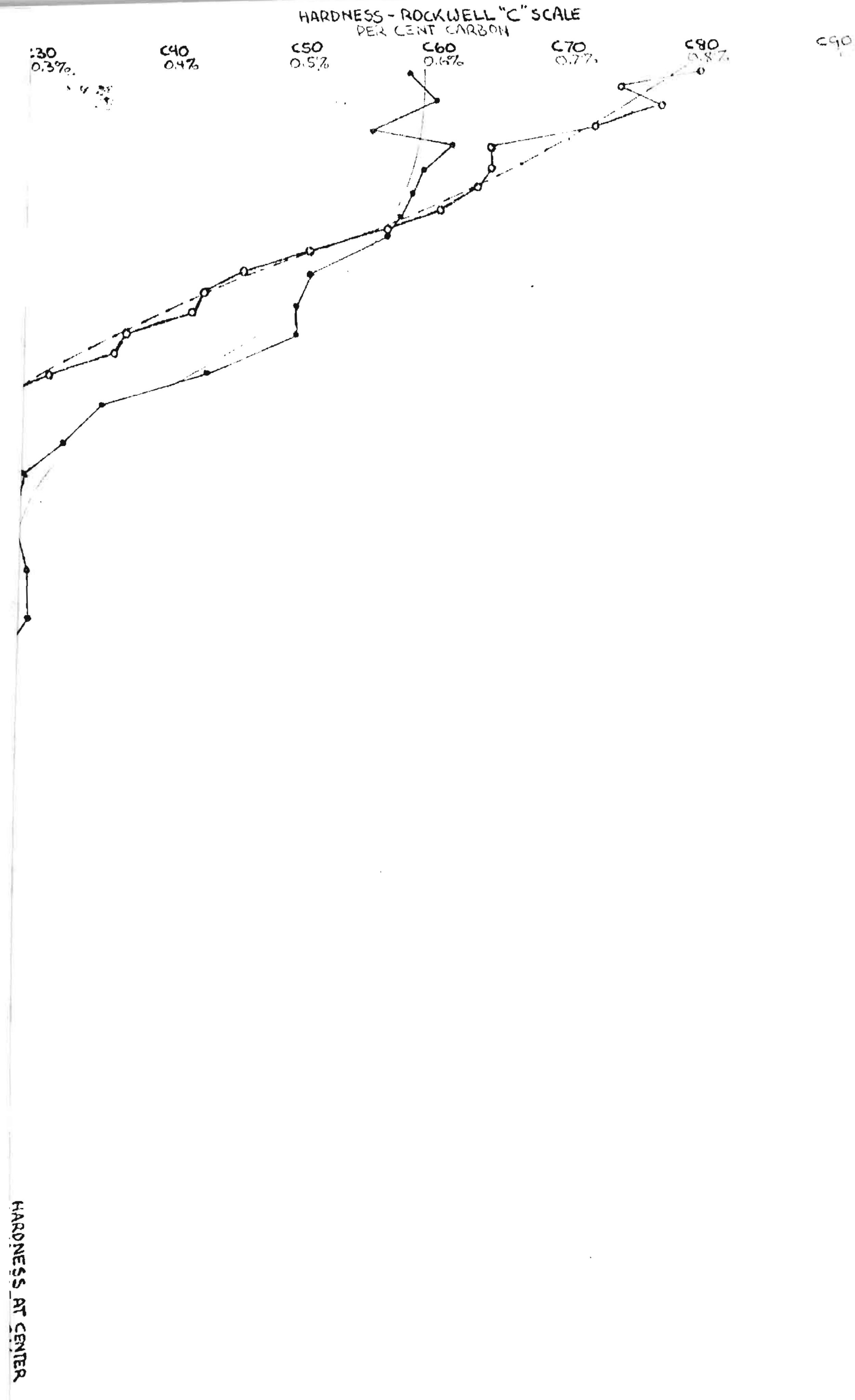
Element	Percent	Element	Percent
C	0.19	Ni	0.40
P	0.02	Si	0.24
S	0.02	Mo	0.24
Mn	0.83	Cu	0.07
Cr	0.53	Fe	Balance

These values are consistent with 8620 steel.

The exposed fracture faces of the sample were damaged severely by rubbing and the mode of failure impossible to detect. A recent article on "Torsional Fractures of Shafts", by Donald J. Wulpi, in the August, 1981, issue of Metal Progress contained some photographs of shafts broken due to reversed torsional fatigue which strongly resembled the shaft under study. A more thorough study of the fracture surfaces was undertaken to see if this mechanism would apply to this sample.

Figure 1 shows the fractured spline shaft with the exposed fracture surface on the left and many unexposed fractures about an inch to the right of the exposed fracture. The cut out portion on the extreme right of the shaft is the section which was removed for elemental analysis and hardness tests. Cuts were made perpendicular to the exposed fracture surface and across the shaft below the unexposed fractures so that some of the unexposed fractures could be broken open and examined. Figure 2 shows the exposed fracture surface after one such section was removed. After examination of a number of these unexposed fracture surfaces, most of which were very badly rubbed, an area was found which appeared to indicate fatigue. This area was placed in the scanning electron microscope (SEM) for a higher magnification examination. Figure 3 is a low mag. SEM which shows two regions with "beach marks" which are typical of fatigue. Figures 4 and 5 are high magnifications SEM's of the fracture surfaces in these regions. There is a hint of fatigue striations in these micrographs and no other fracture mechanism is apparent. Fatigue striations in a steel such as this are often very difficult to see in the SEM.

From all the data obtained it is concluded that this fracture did occur by reversed torsional fatigue as explained in the Metal Progress article which is included with this report. The high stress intensity created by the sharpness of the radius at the base of the spline teeth is the basic cause of failure.


HARDNESS - ROCKWELL "C" SCALE
PER CENT CARBON
C30 0.3%
C40 0.4%
C50 0.5%
C60 0.6%
C70 0.7%
C80 0.8%
C90
HARDNESS AT CENTER

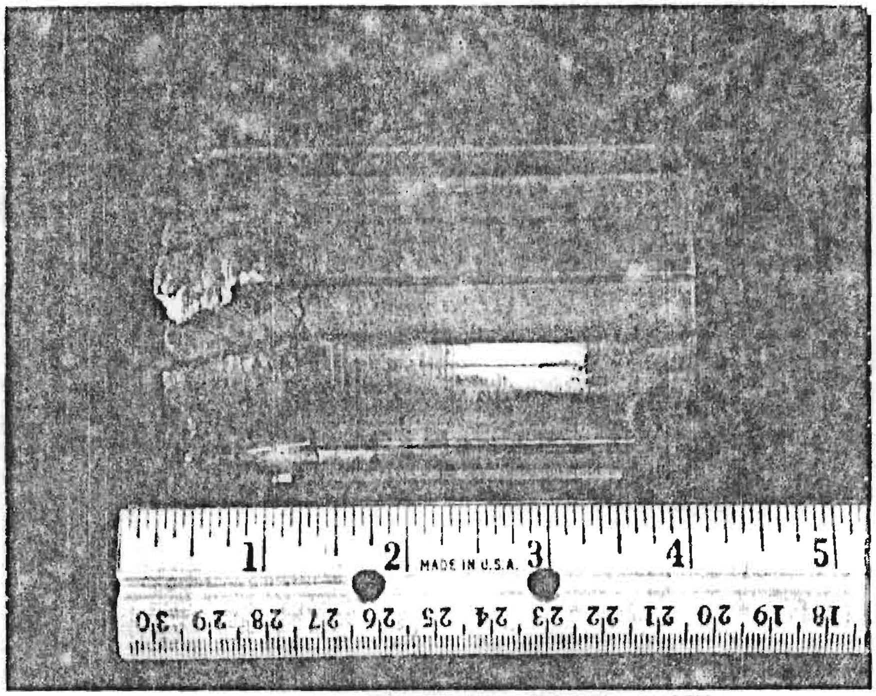


FIGURE 1: FRACTURED SPLINE SHAFT

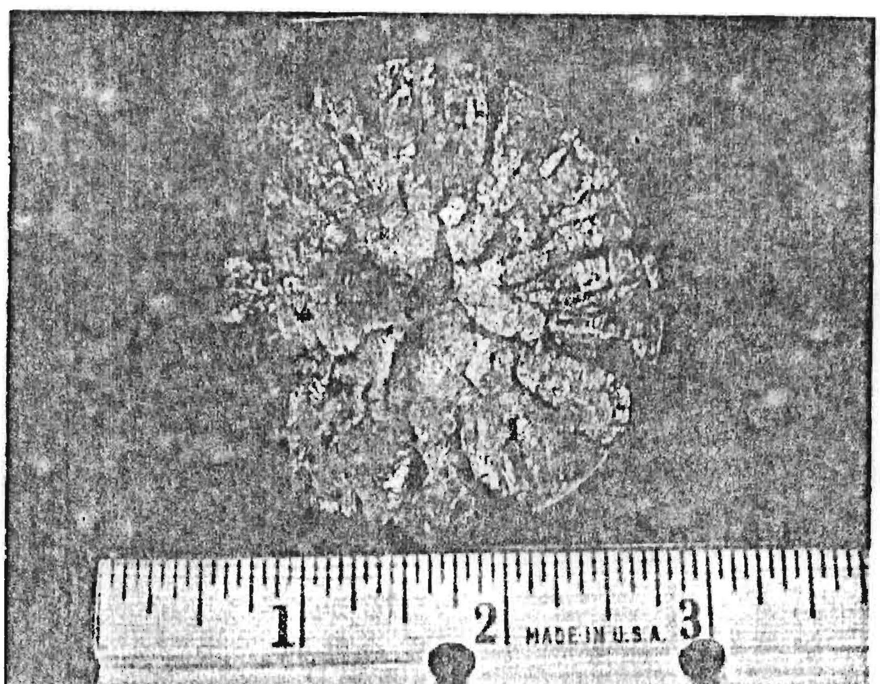


FIGURE 2: FRACTURE SURFACE

FIGURE 3: SEM FRACTURE SURFACE 25X

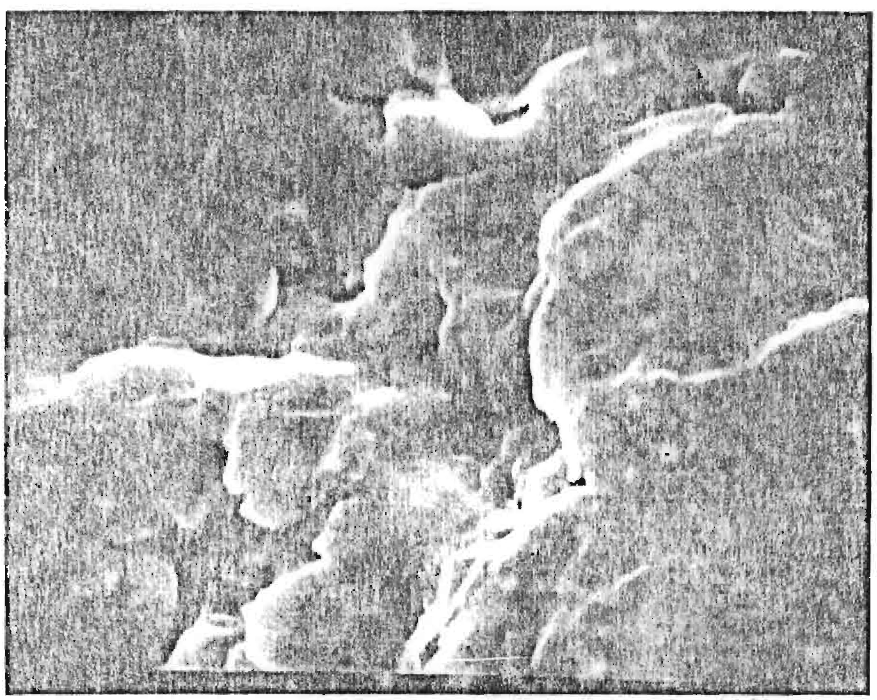


FIGURE 4: SEM OF FRACTURE SURFACE 10,000X

FIGURE 5: SEM OF FRACTURE SURFACE 10,000X

Torsional Fractures of Shafts

By Donald J. Wulpi

AFTER MANY YEARS of studying and analyzing fractures, it has become obvious that the various types of torsional fractures are not well understood. The purpose of this article is to clarify the torsional stress system and to point out significant differences in the types of fractures. Shafts were chosen because they are a very common type of machine element, and they commonly transmit torsional forces.

There are two reasons why torsional fractures are frequently misdiagnosed:

1. The basic stress system acting on a shaft under torsional stress is not well understood.
2. One type of torsional fracture bears a superficial resemblance to a nontorsional fracture.

Some Basics Required for Understanding

To understand how various types of fractures are caused, one must understand the forces acting on the materials as well as the characteristics of the materials themselves. All fractures are caused by stresses, and the weakest link theory applies -- damage will occur when the stress on the weakest element exceeds its strength.

Also, by understanding the ways in which single load, or monotonic, fractures are caused, one can then better understand fatigue fractures, which are the result of many thousands or millions of load applications at maximum stress levels lower than the tensile strength.

To understand the forces, it is necessary to study the stress systems acting on the part. It is very useful to study the stress systems acting on a cylindrical member, such as a rod or shaft. A variety of stresses can be applied to a cylindrical part; also, the same principles can be applied to noncylindrical parts. Shafts and shaftlike parts are very common and are widely used in construction of many assemblies and machines.

Stress systems are best studied by examining free-body diagrams which are simplified two-dimensional models of complex three-dimensional stress systems in the shaft.

Figure 1 shows the orientations of the normal stresses (tension and compression) and the shear stresses (sliding) which are 45° to the normal stresses. Free-body diagrams of shafts in the pure types of loading — tension, torsion, and compression — are the simplest; they then can be related to more complex types of loading. (The free-body diagrams of shafts in pure tension and compression are not considered here for they are covered in the references cited.)

When a shaft is twisted in pure torsion, the stress system — exemplified by the free-body diagram — rotates 45° in one direction or the other to the shaft axis, depending upon which way the shaft is twisted. When twisted as shown in Fig. 1, the tension and compression components are as shown, but will be reversed if the shaft is twisted in the opposite direction. Note that, in either case, the maximum shear stresses are both longitudinal and transverse to the shaft axis. The latter direction, as we shall see, is particularly significant.

As in all fractures, the weakest link will always fail first. Because there are several links, or kinds of strength in metals, there is a kind of race to determine which kind of stress will reach its limiting strength first, thus causing fracture. This, then, is the weak link which is the controlling factor in the behavior of the metal.

In a single, or monotonic, load there are basically two types of metal behavior -- ductile and brittle.

Ductile behavior means that the shear stress has exceeded the shear yield strength and that deformation has taken place because of permanent slippage in the crystal structure. Shear strength is thus the weak link, or controlling factor.

On the other hand, completely brittle behavior indicates that the tensile stress has exceeded the tensile strength and brittle fracture has taken place. Tensile strength is now the weak link. Greatly oversimplified, these concepts are easily understandable and are useful for failure analysis purposes.

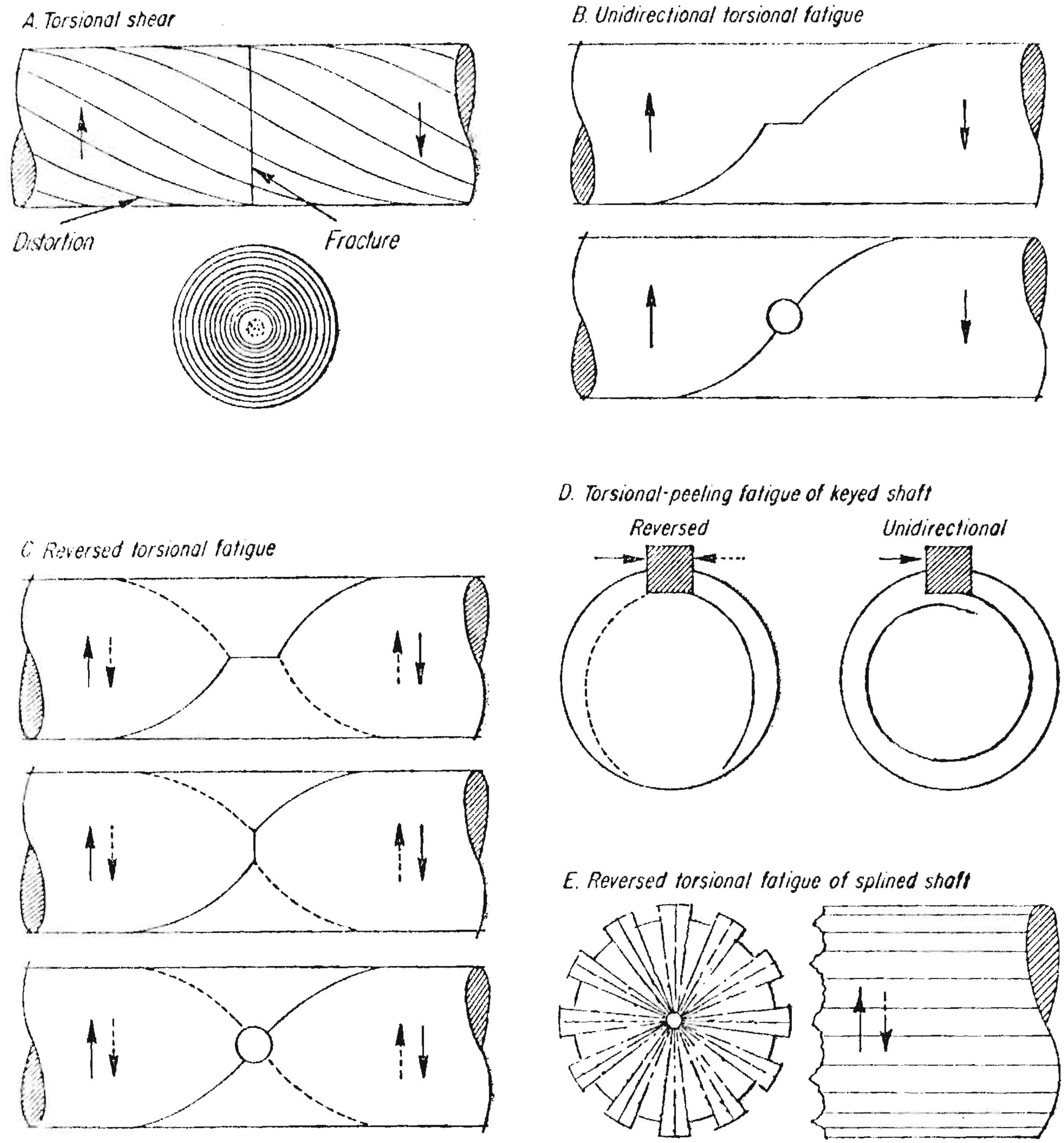
Characteristics of Torsional Overload Fractures

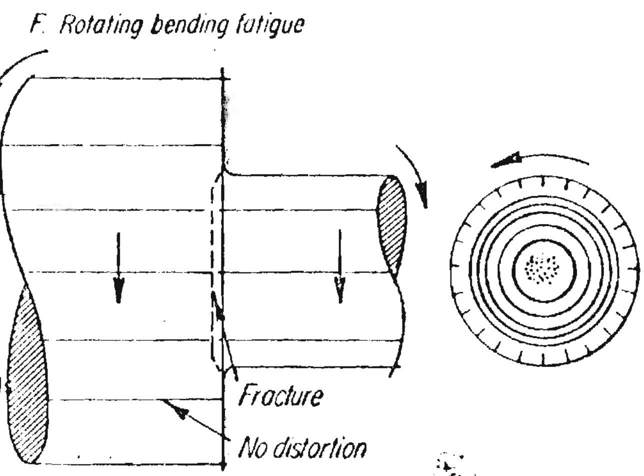
In single overload torsion, as in any other type of loading, one must understand the stress system that caused the part to deform or fracture. Thus, two essential facts must be kept in mind:

1. In torsion, fracture of a ductile material is parallel to the transverse shear stress component; that is, the fracture of a ductile metal in torsion is essentially transverse to the shaft axis, or directly across the shaft.

2. In torsion, fracture of a brittle material is perpendicular to the tensile stress component; that is, the fracture of a brittle metal in torsion is a spiral, approximately 45° to the shaft axis.

As noted, the above discussion has been concerned





Comparison of three types of fracture: torsional shear (A), torsional fatigue (B, C, D, E), and rotating bending fatigue (F). Examples of torsional shear are shown in Fig. 2. Examples of torsional fatigue are shown in Fig. 4, 5, and 6. Examples of rotating bending fatigue are shown in Fig. 3. Although rotating bending fatigue fractures are nontorsional, they do bear a superficial resemblance to torsional shear fractures of ductile metals. The author states, "To understand how various types of fractures are caused, one must understand the forces acting on the materials as well as the characteristics of the materials themselves. All fractures are caused by stresses, and the weakest link theory applies — damage will occur when the stress on the weakest element exceeds its strength."

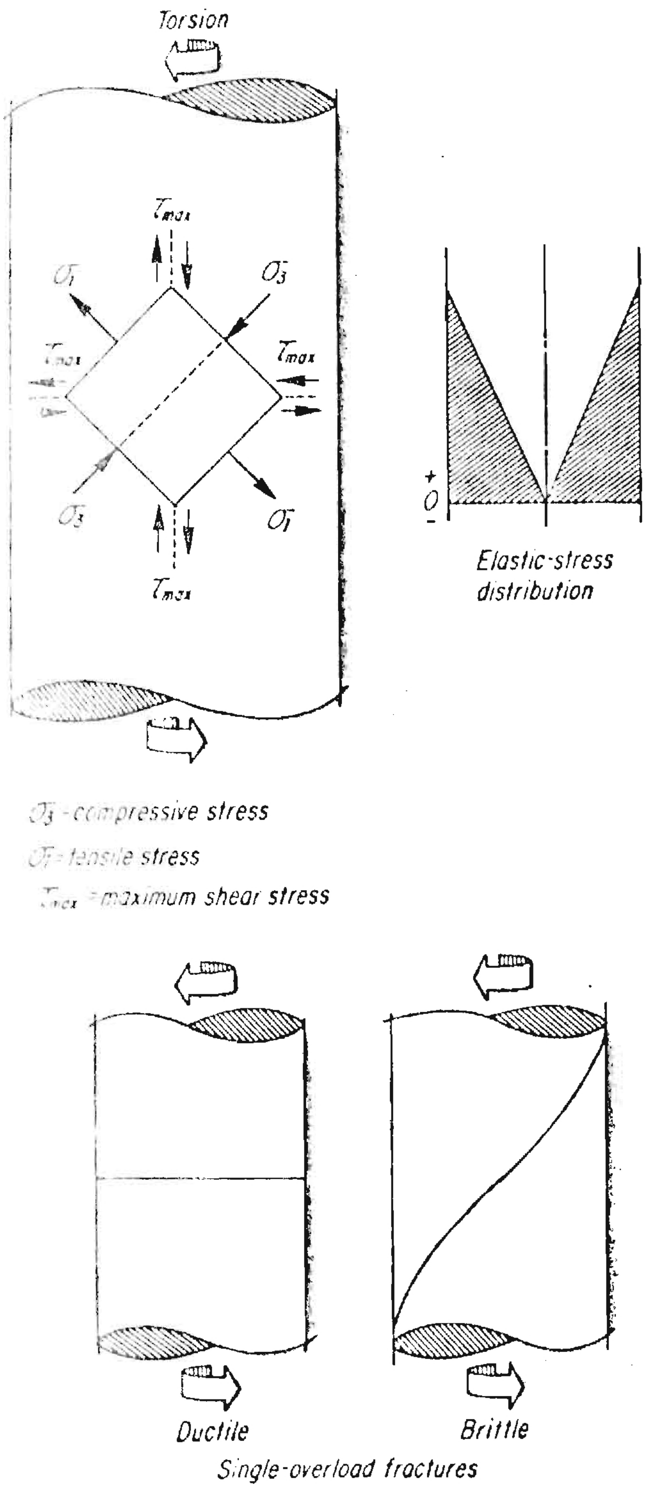


Fig. 1 — Free-body diagram shows the orientation of normal stresses and shear stresses under simple torsional loading. Also shown are the single overload fractures of ductile and brittle materials when loaded in torsion.

with single overload forces. In many service parts they may be caused by extremely high inertia forces encountered during an accident or by jamming of a shaft at the output end while the input force continues. Something has to "give" and the shaft may be damaged in these instances.

Torsional Shear — As pointed out earlier, a single torsional overload fracture of a ductile shaft occurs in the transverse direction — 90° to the shaft axis. The final rupture region is at the center if pure torsion was present, but is offcenter if there was a minor bending force superimposed on the major torsional force. However, the final rupture location is really insignificant compared with the fact that fracture occurred due to a massive torsional overload force that overpowered the strength of the shaft.

One frequently overlooked point is the twisting deformation that accompanies such a transverse shear fracture. This can be visualized by imagining that the shaft consists of an infinite number of infinitely thin discs. When the pack of discs is twisted, each disc slips rotationally a very small distance with respect to its neighboring discs, resulting in spiral deformation that may or may not be obvious. However, the diameter of each disc does not change, nor does shaft length.

If torsional shear fracture occurs in a longitudinally marked area, such as with splines, grooves, or other reference marks, twisting of the shaft will be obvious. However, if fracture occurs in a smooth cylindrical area, twisting deformation will not be obvious unless there were originally straight longitudinal reference marks. Even in this case, it may be possible to etch the metal to reveal twisting deformation in the originally-straight grain flow of a wrought metal.

Figure 2 shows several torsional shear fractures, including small torsion test specimens after fracture; all spiral marks were originally straight prior to twisting.

Torsional Fatigue — In real life, it's usually much more important to prevent fatigue fractures than the occasional, abnormal, accidental forces previously discussed. The reason: fatigue fracture is not caused by massive overload forces, but by normally occurring service forces repeated many thousands or millions of times with varying stress levels and numbers of load cycles during the life of the part.

Fatigue fractures initiate in submicroscopic changes in the crystal structure; these changes occur due to minute slippage, or shearing, that occurs at locations where the local shear stress exceeds the local shear strength after many load repetitions. Because shear is the basic originating mechanism of a fatigue crack, the direction of the original small crack is usually in either the longitudinal or transverse direction of a shaft under repetitive torsional forces.

However, soon after the initial crack is formed, the

Fig. 2A   Driveshaft of 1035 steel (HRC 34) that fractured under torsional overload, twisting off in a fashion that produced a fracture surface almost as flat as if it had been machined (black arrows). A thin slice containing the mating fracture surface was cut (white arrow) from the cylindrical portion and the fracture surface is visible (see disc shaped piece in photo). The remaining shaft portion was hot etched in hydrochloric acid and water to reveal the twisted grain flow and flash lines, which were originally straight but were deformed by the torsional forces when the output side jammed, but the power input continued until the shaft fractured. This plastic deformation is characteristic of torsional shear, but not of fatigue fractures.

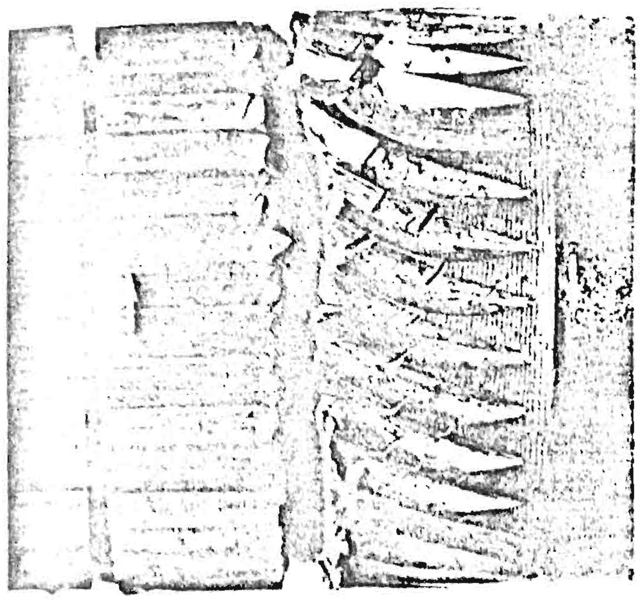


Fig. 2B — Case hardened spline shaft fractured due to a massive torsional force. Fracture is essentially transverse across the shaft, with considerable deformation of the originally straight splines. Note cracking of the relatively brittle thin case in the direction opposite to that of the torsional deformation.

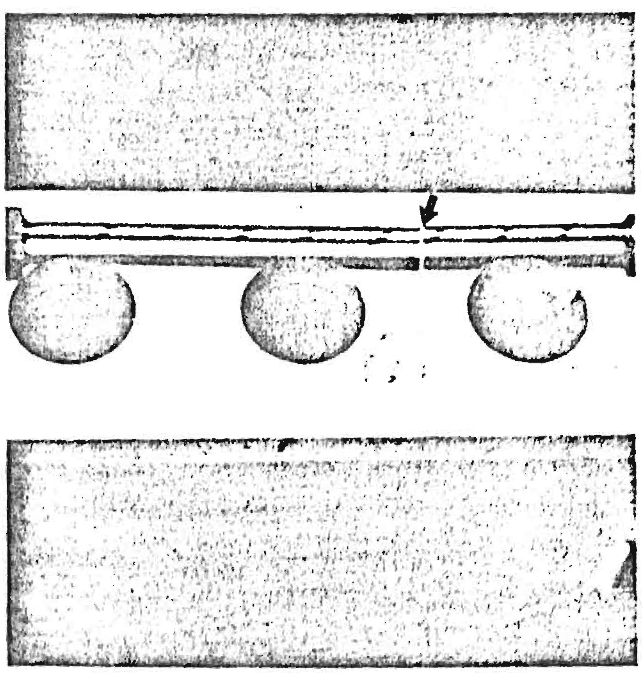


Fig. 2C — Torsional test fixture showing 1/4 in. (7 mm) 1020 steel shaft after fracture (arrow). Black spiral reference mark was a premarked straight line along the shaft prior to rotating from the right side 8 3/4 turns to cause torsional shear fracture.

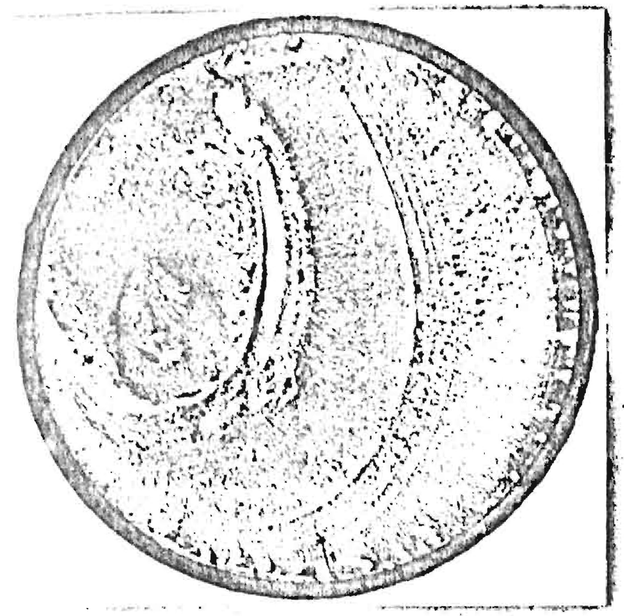


Fig. 3A Surface of rotating bending fatigue fracture of a 1050 steel shaft with a hardness of about HRC 35. Note shiny ratchet marks at the periphery, indicating that fatigue cracks initiated at many locations along a square corner snap ring groove. An eccentric pattern of beach marks is visible, indicating that the part was unevenly loaded or unbalanced. Areas near the fatigue origins are relatively smooth, while those near the final rupture at left are much coarser.

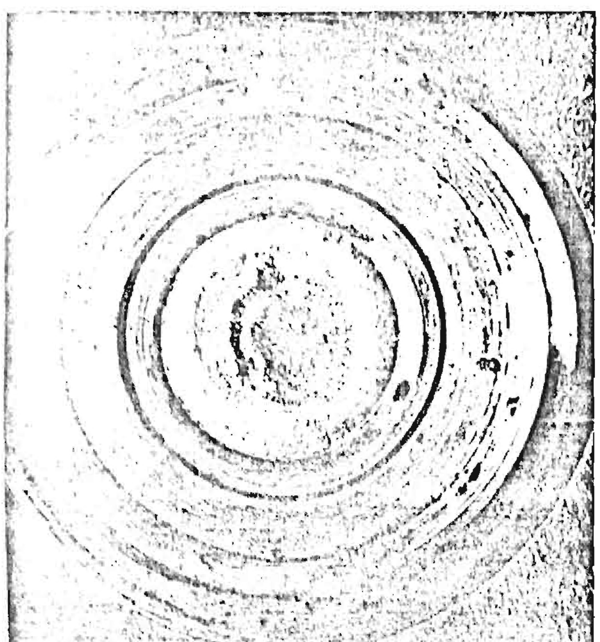


Fig. 3B -- Surface of a rotating bending fatigue fracture in a medium carbon steel shaft with a hardness of HB 143. The part had a large gentle radius in the fillet, but sharp tool marks caused many origins around the periphery, with the fracture dished in toward the large diameter. Final rupture was near the center, indicating that the stress was well distributed.

stress concentration causes the tensile stress component to become dominant. Thus, the propagation of the fatigue crack or cracks turns to become perpendicular to the principal tensile stress component. That is, propagation is in the brittle fracture direction. Because this is at an approximate 45° spiral angle, torsional fatigue cracks propagate in one or many separate spiral directions around the shaft, depending upon the number of fatigue origins.

If final torsional fatigue fracture occurs, it is extremely rough and jagged due to the diagonal cracks which have developed. Some of the projections may become damaged by contact with the opposite side of the fracture. In any case, a true torsional fatigue fracture is never a smooth, transverse fracture, but is very irregular.

A Resemblance — At the beginning of this article, we mentioned that certain nontorsional fractures bear superficial resemblance to torsional shear fractures of ductile metals, as just described. We were referring to fatigue fractures caused by rotating bending forces, not torsion. These also are generally transverse and have a final rupture region that may or may not be at the center of the shaft, depending upon the relative bending forces near the end of fracture.

In addition, characteristic fatigue beach-marks, if present, are roughly circular, or semicircular, and may resemble the rub marks on fracture surfaces of single load torsional shear. However, rotating bending fatigue fractures usually have a few or many radial ratchet marks near the periphery of the fracture. Ratchet marks are actually junctions between adjacent fatigue cracks on different planes.

Comparing Three Different Types of Fracture

Torsional Shear — Fracture usually occurs in a cylindrical section, circular groove, or spline.

The general shape of the fracture is essentially straight across a shaft, although there may be minor projections damaged by contact with others on the opposite side of the fracture (see sketch A on p 24, Fig. 1, and Fig. 2 on p 27).

The fracture surface may be quite smooth or have rub marks concentric around the final rupture. Texture is essentially the same across the fracture surface except for rough final rupture areas. On a micro-scale, the fracture surface is severely deformed in a rotary direction.

Also, there is gross deformation in a spiral direction. The degree of deformation is dependent on the relative length-to-diameter ratio in the location of fracture, as well as the strength (hardness) of the metal. This gross deformation is not obvious, however, unless there were longitudinal reference marks on the shaft prior to torsional overloading.

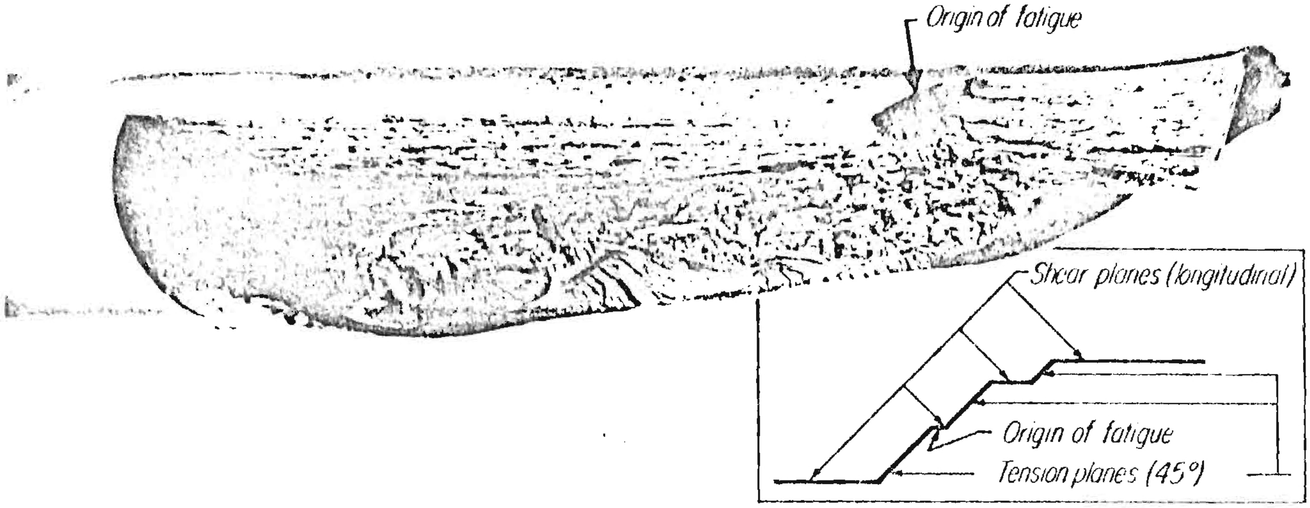


Fig. 4A — Surface of a torsional fatigue fracture in the cylindrical portion of a 1 3/8 in. (35 mm) diameter torsion bar spring of 50B60 steel heat treated to HRC 53. The fatigue crack originated in a very small (0.015 in. [0.4 mm]) longitudinal shear plane and propagated alternately on 45° tension planes and longitudinal shear planes, as indicated in the diagram. Note that the semicircular fatigue area surrounding the origin lies in the 45° plane.

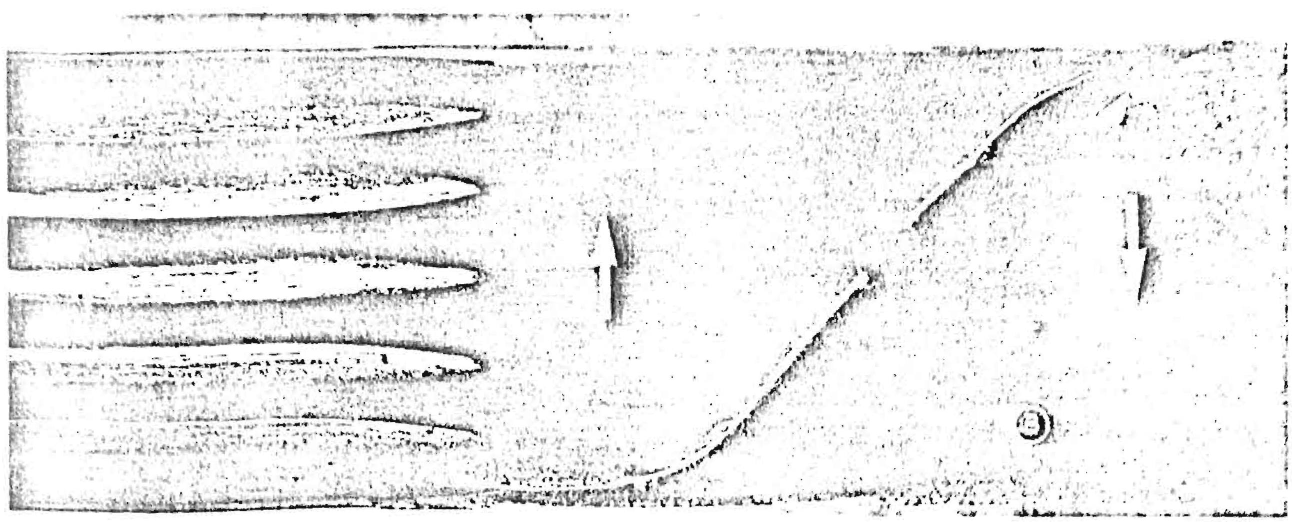


Fig 4B — Surface of shaft with a torsional fatigue fracture originating at a transverse hole which acted as a stress concentration in a case hardened steel which had a surface hardness of about HRC 60. Note that the fatigue crack was at the characteristic 45° angle as it progressed in both directions from the hole. (Crack visibility was enhanced with iron powder.)

Torsional Fatigue — Fracture may be in the same location as in torsional shear, but is frequently different. In this instance, there may be a sensitivity to stress concentrations such as transverse holes and longitudinal grooves.

Fractures take a large variety of shapes, depending on the geometry of the shaft and loading directions. If torsion is unidirectional, there will usually be one long spiral crack (about 45°) with a longitudinal or transverse shear origin (see sketch B on p 24 and Fig. 4 on p 29). However, if the origin is in a stress concentration, there may be no obvious origin.

If reversed torsion were present, the surface will have approximately 45° spiral cracks at opposite diagonals. Multiple origins will cause multiple pairs of V-shaped diagonal cracks to form individual segments. (See sketches C, D, E on p 24 and Fig. 4 through 6 on p 29-31. Also check these crossreferences: Fig. 5 for sketch C; Fig. 6C for sketch D; and Fig. 6A and 6B for sketch E.)

Individual fatigue facets near the fracture surface may be quite smooth despite a multitude of projecting surfaces. Fatigue facets are usually damaged by rubbing of the opposite side of the crack during propagation or after fracture has occurred.

There is little or no deformation of metal near fatigue origin areas, although the final rupture area may have deformation.

Rotating Bending Fatigue — Fracture usually originates in a groove, fillet, hole, or other stress concentration that is at least partially transverse to the shaft axis.

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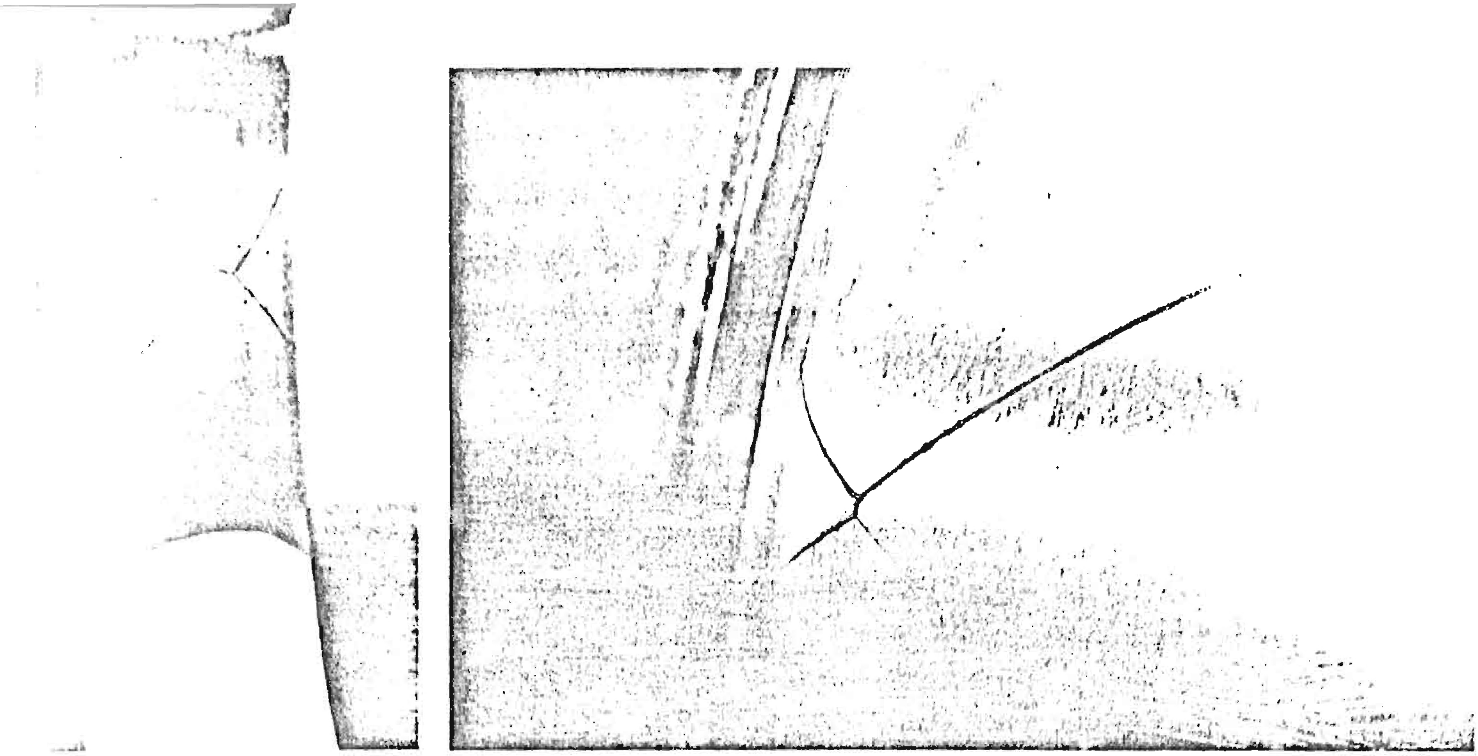


5A 5B

Fig. 5A — Closeup of a reduced area on a medium carbon steel driveshaft, intended to serve as a location for single overload torsional shear. However, reversed cyclic torsional stresses caused the part to crack in fatigue without a massive torsional overload. The original crack was in the longitudinal shear plane. Each pair of torsional cracks developed at a 45° angle to the shaft axis. Fig. 5B — Reversed torsional fatigue cracks in a 1045 steel crankshaft that was tested in the lab. Visible at base of fillet is fatigue crack that originated in the transverse direction. Again, each pair of torsional cracks developed at a 45° angle to the shaft axis. Fig. 5C — Surface of fatigue fracture in an induction hardened 1050 steel axle at about HRC 50. Tested in

The general shape of the fracture is essentially straight across the shaft but is curved or dished inward toward the larger diameter if the fracture originates in a circular corner or fillet. (See sketch F on p 24 and Fig. 3 on p 28.)

There may be many radial ratchet marks near the surface of the shaft, each of which is the junction of two fatigue origin areas. Fracture is generally smoother near the periphery and coarser toward the final rupture area.

There is little or no deformation of metal near the fatigue origin areas, although the final rupture area may have deformation. Twisting, or spiral deformation, is absent.

For More Information: You are invited to contact the author directly by letter or telephone. Mr. Wulpi, FASM, is a metallurgical consultant and may be reached at 3919 Hedwig Dr., Ft. Wayne, Ind. 46815; tel: 219/485-4853.

References

"Interpretation of Light-Microscope Fractographs," by John A. Fellows et al: *Metals Handbook*, 8th Ed., Vol 9, American Society for Metals, Metals Park, Ohio, 1974, p 36-37.

"Failures of Shafts," by Herman D. Greenberg et al: *Metals Handbook*, 8th Ed., Vol 10, American Society for Metals, Metals Park, Ohio, 1975, p 375-379.

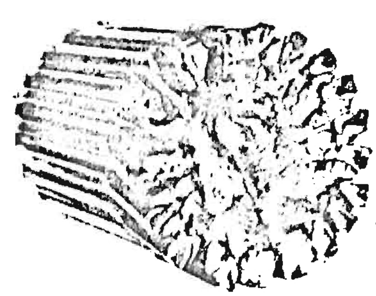
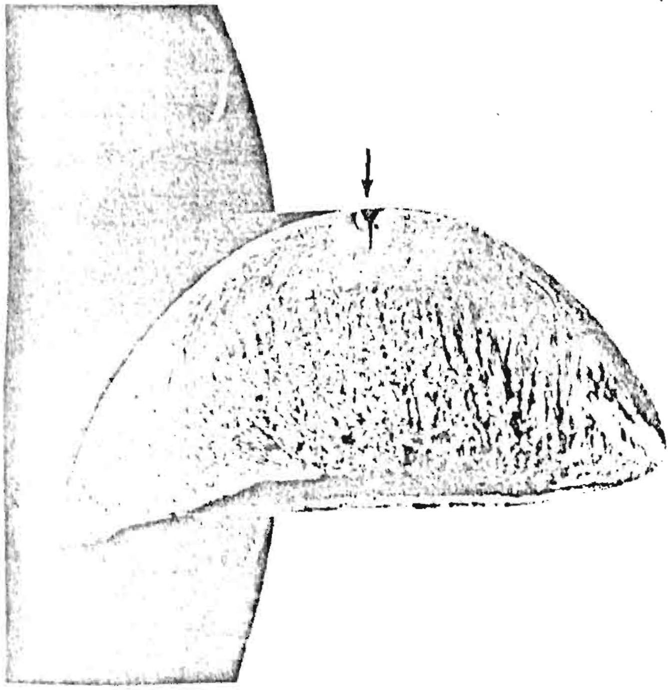
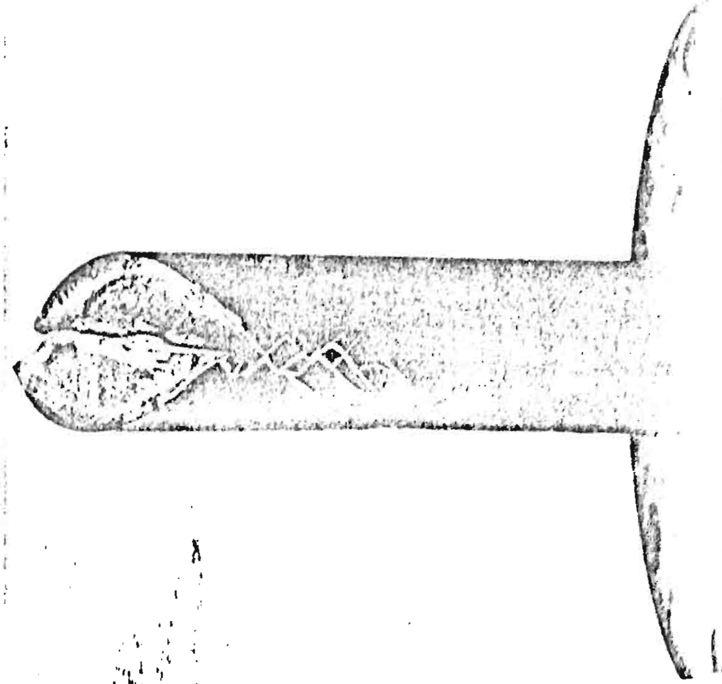


Fig. 6A — Splined shafts frequently fail in reversed torsional fatigue in a characteristic manner to produce a starry fracture due to a large number of fatigue origins, usually at the inner corner of each spline tooth, which acts as a stress concentration. This results in many small 45° cracks, two for each spline tooth. Each small crack is 90° to its neighbor. As the cracks progress inward, they tend to surround longitudinal volumes of metal with cracks, for the same thing is happening farther along the shaft at the opposite end of the spacer which is usually present.



5C



5D

partially reversed torsion, the fatigue crack originally started in the longitudinal shear plane. It then changed to the characteristic 45° direction and grew in fatigue to the size of the small circular beach mark or halo. At that time it reached its critical flaw size and final brittle fracture occurred under a single torsional load. Fig. 5D — Fatigue fracture of a 1 1/2 in. (38 mm) in diameter axle of 1045 steel induction hardened and tempered to HRC 52 and tested in reversed torsional fatigue. It shows fatigue cracks on the diagonal planes of maximum tension stress. Secondary cracks revealed by the iron powder patterns on the magnetized axle are symmetrical, indicating that the stresses applied during the test were fully reversed.

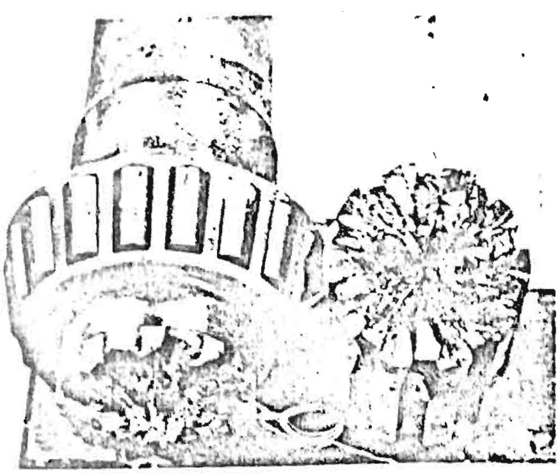


Fig. 6B — A splined shaft can also fracture due to reversed torsional fatigue at the spline runout, as is seen here. This starry fracture also has the multiple fracture origins, each of which has the characteristics of fatigue. The number of actual fatigue cracks is thus double the number of spline teeth — 20 cracks in this instance.

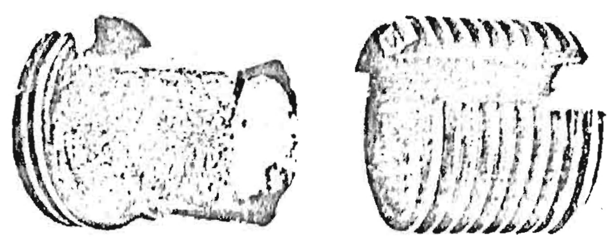


Fig. 6C — Another specialized type of fatigue fracture due to reversed torsional stresses is the peeling fracture. This keyed shaft developed two fatigue cracks, one on each side of the keyway. These continued inward around the shaft because the nut on the threads prevented the crack from reaching the surface. Eventually, the two cracks met on the opposite side, permitting the shell to separate from the shaft. The steel was a cold drawn, resulfurized grade with medium carbon content.